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GRADUATE FELLOWSHIP IN HYPERSONICS

FINAL REPORT

by
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A graduate fellowship in hypersonics was awarded to Paul D. Orkwis for study at North Carolina State University. Research was performed in cooperation with the U. S. Army Ballistic Research Laboratory to develop innovative means of computing flow over sustainer projectiles at high speed.

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A code was developed using Newtons iteration applied to the steady Navier-Stokes equations. Roe's upwind flux difference splitting was used for spatial discretization. Second order accurate values of the Riemann variables were obtained by Spekreijses interpolation procedure with Van Albada's limiter used to reduce spurious oscillations in the results. The Jacobian derivatives and the code necessary to compute the Jacobian elements were generated by use of the symbolic manipulation code MACSYMA. The Boeing package RSLIB was used to invert the Jacobian matrix.

Computational results were obtained for flat plates, flat plate-ramp, and ogive-tangent-cylinder configurations at Mach numbers ranging from 2 to 14.1. These cases contained shock on shock interactions, viscous layer separations, and turbulent boundary layer transitions. Convergence was obtained in 15 to 200+ iterations. The results agreed well with experiment or other computation and demonstrated that Newton iteration can produce results for complex high speed flows with shock waves.

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Introduction

This document comprises the final technical report for ARO Grant DAAL03-86-G-0039, "Graduate Fellowship in Hypersonics." The fellowship was awarded to Mr. Paul D. Orkwis after national advertisement. Mr. Orkwis completed the Requirements for the Ph.D. degree on November 5, 1990 and will be awarded this degree at NCSU's December 19, 1990 graduation. He has accepted a position as Assistant Professor in the Department of Aerospace Engineering at the University of Cincinnati beginning in January 1991.

The remainder of this document will discuss the research problem addressed and will present a brief summary of research results. A list of publications and presentations of the work is included.

Research Problem

The Ballistic Research Laboratory (BRL) at the Aberdeen Proving Ground has been studying a class of ballistic "sustainer" projectiles which seek to reduce drag by igniting gas-producing solid fuel in the base of the projectile. In cooperation with BRL, developing innovative means for computing flow over these projectiles was chosen as the research project for this fellowship. BRL personnel have kindly supplied advice and computational resources in support of the project.

These projectiles are essentially secant-ogive-cylinder-boattail (SOCBT) shapes[(1)] with a bluff base region where the combustion products are injected into the flow. The projectiles travel at supersonic speeds at a small angle of attack during their trajectory. This presents a difficult computational problem in that the flow is three-dimensional and the governing equations are very stiff due to the source terms and the widely varying eigenvalues in the free stream and base regions. Research was initially directed toward finding means of integrating the governing equations accurately and efficiently in spite of this stiffness.

Research Results

Fishers equation provides an excellent model problem for testing integration techniques for the Navier-Stokes equations with source terms. Fishers equation has both diffusive and source

terms and has an exact solution for comparison with the computational results. A combined integration technique was applied to this equation to allow complete freedom to vary the integration technique continuously between fully explicit and fully implicit. The scheme was also applied such that the discretization of the diffusion term and source term could be different. A large number of discretization combinations were tried for various marching step and source term magnitudes. Results obtained for fully explicit discretization were accurate for small source terms with time steps less than or equal to the stability limit but were of course unstable for larger time steps. Trapezoidal (TR) differencing was found to match the small timestep fully explicit results but with significantly higher timesteps. Fully implicit (FI) differencing also allowed large timesteps but resulted in significant phase errors. This study found that the most accurate and efficient technique for diffusive equations with source terms was the TR differencing.

Studies were then performed with the TR and FI schemes on more Navier-Stokes-like model equations. Stability and modified equation analyses of the linear Burgers equation showed that virtually unlimited timesteps could be used with the FI scheme but not with the TR differencing. These results indicated that the most efficient way to obtain a solution of given accuracy of the linear Burgers equation was to use the FI scheme with as large a timestep as possible. Convergence in as little as 2 iterations was obtained with the FI scheme.

Tests were then conducted using the FI scheme for the nonlinear Burgers equation: which indicated that reduced iteration counts would result from using large timesteps. However, obtaining a given level of convergence could not be guaranteed for the nonlinear equation set. It was determined that this difficulty was the result of applying a solver designed for linear problems to nonlinear equation sets. Fortunately, a corresponding solver for nonlinear equation sets does exist: Newton's method. This method was then used for the next steps in the model problem hierachy, the Euler equations and finally the Navier-Stokes equations.

The Newtons method integrates the full steady Navier-Stokes equations. An algebraic turbulence model is included to simulate fluid turbulence where appropriate. Newtons method as used in the present work[2] can be written

$$\frac{\partial F(\bar{U})}{\partial \bar{U}} \Delta \bar{U} = - F(\bar{U})$$

where $F(\bar{U})$ is the set of discretized Navier-Stokes equations and the vector $\bar{U}$ consists of the conserved variable vectors at each point in the discretized domain. The Jacobian Matrix $\frac{\partial F(\bar{U})}{\partial \bar{U}}$ is taken after discretization of the equations and is exact without approximation in the present work. Roes flux difference splitting was used to discretize the equations since an analytical expression for the spatial discretization was necessary to obtain an exact Jacobian. Spekreijse's interpolation procedure was used to obtain the left and right states for Roe's method to second order accuracy. Van Albada's limiter was used to prevent non-physical oscillations in the solution.

The symbolic manipulation code MACSYMA was used to perform the differentiations and output the FORTRAN code necessary to compute the elements of the Jacobian matrix. MACSYMA macros were written that produced the approximately 8000 lines of code necessary for each differencing stencil in approximately one hour of mini-computer time. The use of MACSYMA allowed very rapid formulation changes and guaranteed that the code was error free.

The Newton iteration procedure was performed by successively inverting the Jacobian matrix, solving for $\Delta\bar{U}$ and then updating $\bar{U}^{n+1}$ and the Jacobian. No attempts were made to accelerate convergence due to complexity of the compressible flowfields with shock waves. The code RSLIB developed at Boeing was modified to be used with the ILU(Ø) iterations and was used to perform the inversion of the sparse Jacobian matrix.

A time term was added to the diagonal of Newtons method to allow initial guesses for the solution that were not "close" to the final solution. This term essentially made Newtons behave like a backwards Euler formulation that would approach Newtons method as the time term was increased. Slug flow initial conditions could then be used without difficulty. A procedure based

on the norm of the residual was developed to increase Δt automatically during the iteration procedure. Further details of the method and iteration procedure are available in References 2, 3 and 4.

Computational results were obtained for flat plate, flat plate-ramp, and ogive-tangent-cylinder (OTC) configurations at Mach numbers from 2.0 to 14.1. These cases contained laminar and turbulent viscous layers, separated regions, shock on shock interaction and strong expansions. Convergence to a residual value of 10^{-7} was obtained at iteration counts ranging from 16 to 217 iterations. A discussion of two of these cases follows.

A flat plate-ramp configuration tested experimentally by Holden and Moselle has been used often for code verification. Flow at ramp angles of 15° and 18° contain separated flow regions (18°) and shock on shock interactions (15° and 18°) to provide a severe test case for Newton iteration. Results were obtained for the 15° case using an 103 x 40 grid comprised of three overlapping 40 x 40 grids in 38, 62, and 106 iterations respectively. Examination of the computational results revealed excellent agreement with the experimental pressure distributions and good agreement with the experimental skin friction distribution for both the 15° and 18° (which used a 142 x 40 grid and required 38, 76, 162, and 69 iterations respectively) cases.

Flows over the OTC configuration tested experimentally in ref (1) were also computed. Five overlapping grids of 40 x 40 were used for an overall 176 x 40 grid. The axisymmetric equations proved to require more iterations to converge the solution and also required the addition of Harten's eigenvalue correction to remove difficulties encountered at the sharp nose of the projectile. The surface pressure data agreed well between experiment and computation except near transition. Further work is needed to investigate relaxation models in this region.

Concluding Remarks

This work provides the initial demonstration that Newton iteration can be used to obtain computational results for complex compressible flows including strong shock waves. It has also been demonstrated that the code to compute exact Jacobians can be easily obtained through use of MACSYMA to allow rapid generation of code for new formulations. Newton iteration is not yet

competitive in efficiency with standard time marching techniques. However, future research should improve efficiency by use of convergence acceleration and improved sparse matrix inversion packages.

Scientific Personnel Supported

Paul D. Orkwis, Graduate Fellowship Recipient
D. Scott McRae, Ph.D., Associate Professor, NCSU, 5% release time donated by NCSU

Degrees Awarded

Paul D. Orkwis - Ph.D., December 19, 1990

Publications

Orkwis, Paul D., "A Newtons Method Solver for the Two-Dimensional and Axisymetric Navier-Stokes Equations," Ph.D. dissertation, N. C. State University, Raleigh, NC November 1990.

Orkwis, Paul D. and McRae, D. S., "A Newtons Method Solver for the Navier-Stokes Equations," AIAA paper 90-1524, Seattle Washington, June 1990 (also submitted to the AIAA Journal).

Orkwis, Paul D. and McRae, D. S., "A Newtons Method Solver for the Axisymmetric Navier-Stokes Equations," submitted to the AIAA 10th Computational Fluid Dynamics Conference, Honolulu, Hawaii, June 1991.

Presentations of the Research

Orkwis --
1990-McDonnell Douglas Research Laboratory, St. Louis, MO
1990-United Technologies Research Center, Hartford, CT
1990-University of Cincinnatti, Cincinnati, OH
1990-ARO, Research Triangle Park, NC

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(3) Orkwis, Paul D. and McRae, D. S., "A Newtons Method Solver for the Navier-Stokes Equations," AIAA Paper 90-1524, Seattle Washington, June 1990 (also submitted to the AIAA Journal).

(4) Orkwis, Paul D. and McRae, D. S., "A Newtons Method Solver for the Axisymmetric Navier-Stokes Equations," submitted to the AIAA 10th Computational Fluid Dynamics Conference, Honolulu, Hawaii, June 1991.